Chapter 11.

Forest Mensuration with Remote Sensing:

A Retrospective and a Vision for the Future

Randolph H. Wynne [1]

Abstract—Remote sensing, while occasionally oversold, has clear potential to reduce the overall cost of traditional forest inventories. Perhaps most important, some of the information needed for more intensive, rather than extensive, forest management is available from remote sensing. These new information needs may justify increased use—and the increased cost—of remote sensing.

INTRODUCTION

Forestry Information Needs of the 21st Century: Increasing Demand and a Changing Landscape

Demand for forest products is expected to increase rapidly during the 21st century. Population growth and economic development that increase the per capita consumption of forest products drive this trend. Global population, now approximately 6 billion, is estimated to increase by 900 million each decade for the next 50 years (Food and Agriculture Organization of the United Nations 1997). Most of this increase will occur in developing nations. Level of economic development strongly affects the demand for forest products. Worldwide income measured as gross domestic product increased by 109 percent between 1970 and 1994 (Food and Agriculture Organization of the United Nations 1997). Gross domestic product is estimated to rise from $20 trillion in 1990 to $69 trillion in 2030, with the most dramatic increases occurring in the developing nations (World Bank 1992).

Although the demand for forest products is increasing, global forest area is decreasing. Between 1985 and 1995, the area of the world's forests decreased by 180 million ha, an annual loss of 18 million ha (Food and Agriculture Organization of the United Nations 1997). Much of this loss resulted from the conversion of forest land to nonforest uses such as agriculture, pasture, or development. Environmental regulations and the desire to preserve native forests to maintain biodiversity further restrict harvesting of forest products. For example, harvest of timber from the national forests in the United States decreased from 12.0 billion board feet in 1989 to 3.5 billion board feet in 1997 as the focus of the U.S. Department of Agriculture Forest Service shifted from timber production toward wilderness preservation, protection of habitat for threatened and endangered species, watershed protection and restoration, and recreation (U.S. Department of Agriculture, Forest Service 1998).

Industry Trends Affecting Remote Sensing

Many forest industry trends will affect the future of remote sensing in forestry. Some of the most important are as follows:

- Smith and others (2003) note that industrial forest landowners have moved from an exclusive emphasis on supplying fiber toward a view of forest land as a biological asset that must be managed financially. If this is true, additional information inputs, such as remote sensing, that increase financial returns might well be justified.
- As noted earlier, industrial forest management is increasing in its intensity, partly because there has been an effective decrease in the amount of public land available for active management. It can make economic sense to spend more for information about the forest resource if the additional expenditure decreases the overall cost of inputs, particularly in the establishment and early growth phases.
- Information available from digital remote sensing can now be combined with other digital geospatial information to provide a complete scheduling picture from site preparation to harvest scheduling within an organization.

[1] Associate Professor, Virginia Polytechnic Institute and State University, Department of Forestry, College of Natural Resources, Blacksburg, VA 24061.

Chapter Overview

Remote sensing has been actively integrated into forest inventory and management systems for more than half a century. The methods used now are still effective, but there is much potential for increased use of remote sensing both for traditional inventory purposes and to provide the information necessary to increase forest productivity. This chapter starts with a retrospective view of photo mensuration, and this is followed by a brief discussion of lidar remote sensing, one of the more promising new technologies for collecting data for forest inventory and monitoring. The discussion of lidar remote sensing is followed by an example that shows how information obtained by remote sensing could increase productivity and, thus, justify increased expenditure for information. The chapter closes with a brief discussion of barriers that must be overcome before remote sensing data are transformed into information directly useful to foresters.

WHERE WE HAVE BEEN: PHOTO MENSURATION

Vertical aerial photographs, while used in forestry since the late 1920s (particularly in Quebec and Ontario, Canada) (Spurr 1960), have been commonly used by foresters in the United States since the 1940s (e.g., Lund and others 1997). Forestry applications of aerial photography have been diverse, covering most aspects of the private and public goods provided by forests. However, a primary driver for forest photogrammetry has been forest mensuration, classically defined as "the determination of dimensions, form, weight, growth, volume, and age of trees, individually or collectively, and of the dimensions of their products" (Helms 1998). Substantial effort has gone into ways of using photographs as a means of determining volume by species accurately, precisely, and at the lowest possible cost. This effort has been reasonably successful, but applications of aerial cruising (e.g., Avery 1978) are becoming significantly less common in the United States, although quite common elsewhere (e.g., Canada).

There are several possible reasons for the decline of photographic mensuration. These can be summarized as follows:

1. The precision of photographically derived volume estimates is not as high as that of field-derived volume estimates.
2. Photographic interpretation and photogrammetry require specialized skills that are increasingly being supplanted by other ones, such as skills in the use of Geographic Information Systems (GIS), in accredited forestry programs (Sader and Vermillion 2000). This is occurring despite results from the most recent survey of desired entry-level competency and skill requirements which show that more entry-level forestry positions require knowledge of aerial photos (68 percent) than GIS (43 percent) (Brown and Lassoie 1998).
3. In much of the United States, forest land parcel size is steadily decreasing and accessibility increasing, thus decreasing the economic justification for (or even the feasibility of) photo mensuration.
4. Research in forestry remote sensing now focuses on actual and potential applications of newer airborne and spaceborne sensors, such as radar, lidar, and high-resolution digital optical sensors.
5. Wide use of medium-resolution spaceborne sensors such as the Landsat Multispectral Scanner and Thematic Mapper that are inherently digital has led to an expectation of ever more automated approaches to information extraction. Most algorithms in operational use are based almost entirely on the use of discriminant functions to categorize the brightness value vector from each pixel, even though this approach makes use only of hue. Hue is just one of the nine commonly identified elements of image interpretation, the others being shape, size, pattern, texture, association, shadows, resolution, and site (Olson 1960).
6. The actual or perceived benefits of using photos for inventory may be less than the costs incurred.

The last of these points is the most important, since we can assume that forest managers and scientists are obtaining the information needed without widespread use of ordinary photography. However, demands on forests are increasing, and the information required to sustainably manage forests in the face of this demand must also increase. Foresters are being asked to increase production of wood and fiber on an ever-decreasing land base while maintaining the important supplies of public goods (viable fish and wildlife populations, clean water, and recreational opportunities) that well-managed forests have always provided. To meet this challenge, forest managers will require new types of information, and remote sensing will help to supply these. If remote sensing fills our requirements, we will need to evaluate previous successes and failures and work to improve the match between information that can be objectively and accurately derived from remotely sensed data and the information needed for forest management (Wynne and others 2000).

Aerial Cruising

Aerial (photo) volume tables have been constructed for both individual trees and stands (Avery 1978). All are based on total tree height and visible crown diameter for individual trees. For stands, volume tables use stand height and percent crown closure at a minimum; many also include visible crown diameter classes. These tables use visible crown diameter as a surrogate for stem diameter and percent crown closure as a surrogate for basal area or stem density.

Tree heights are typically measured by stereoscopic parallax methods that employ a parallax bar or wedge and large-scale photographs. Shadow lengths can be used where terrain is level and stands are relatively open. While the accuracy of these measurements varies, on 1 inch = 20 chains photography, the average difference between ground- and photo-measured tree heights (with well-trained interpreters) is typically about 1 foot (Spurr 1960).

Visible crown diameter is measured with either a micrometer wedge or a dot-type scale. It can be argued that crown diameter is more accurately measured on large-scale photographs than on the ground, but measurements made on photographs are not directly comparable to those made on the ground because in photographs (1) only the dominant overstory trees are visible, and (2) the edges of any particular crown are obscured by the crowns of adjacent trees. For these reasons, photo-derived visible crown diameters are always underestimates of actual crown diameter. Even given these limitations, however, photo-measured visible crown diameter is often better correlated with actual tree and stand volume than field-measured crown diameter, because it is a measure of the tree's functional growing space (Spurr 1960). Measurement consistency varies widely with conditions, but can be expected to be on the order of 3 to 4 feet two times out of three on 1:12,000 photos (Paine 1981), which is why most volume tables are based on 3- to 5-foot diameter classes.

Percent (overstory) crown cover is the most subjective of the three direct forest measurements made from aerial photographs. It can simply be ocularly estimated or (more commonly) ocularly estimated with the aid of crown density scales. It usually is an overestimate of actual crown cover, because small canopy gaps are often not visible and shadows are often treated as trees. When typical forestry photo scales are used, standard errors do not exceed 10 percent, but the bias of an individual interpreter commonly ranges from 5 to 10 percent (Spurr 1960).

However, volume estimates derived by using stand photo volume tables are too imprecise for many uses, as standard errors of the estimate are likely to exceed 25 percent (Spurr 1960). While standard error can be reduced by increasing the number of samples, stand photo volume tables are also biased, requiring double sampling with regression using matched field- and photo-measured plots (e.g., Paine 1981). This casts doubt on the economic feasibility of photo mensuration for the smaller tracts that are increasingly common.

To summarize, timber volume can be estimated from aerial photographs. Bias exists because (1) a vertical aerial photographs image-only portions of the crowns of dominant overstory trees; and (2) subjectivity, particularly in crown closure estimation, leads to interpreter-specific bias. The latter bias also leads to unacceptably high standard errors of the estimate. Substantial training that is increasingly hard to obtain is required to make accurate direct tree and stand measurements based on aerial photographs. All these factors combined make the use of aerial inventory cost-effective primarily for large, relatively inaccessible areas.

Stratification

At this point one might reasonably ask why acquisition of photography is still so routine in many organizations charged with managing forest lands. The answer is, in part, that photos are used for more than just aerial timber cruising. Other uses include forest mapping for management planning, stress detection, forest area estimation, and land navigation, particularly in remote and infrequently mapped areas. These uses, however, are often secondary in comparison to the routine use of photos to stratify timber cruises. Stratification refers to “the subdivision of a population into strata (subpopulations) before sampling, each of which is more homogeneous for the variable being measured than the population as a whole” (Helms 1998).The advantages of stratification include (1) more precise estimation of the population mean (given properly constructed strata), (2) separate estimates for each subpopulation, and (3) reduced costs (Avery 1978, Avery and Burkhart 2002). As Avery and Burkhart note (2002), photographs are commonly used in stratified sampling to measure area, allocate field samples by volume classes, and plan fieldwork. For many organizations, photo acquisition can be justified by stratified sampling alone. This stratified sampling not only improves precision and reduces cost, but also changes the flow of information within an organization, with the result that there is a two-way flow between field personnel and the organization’s information systems.

WHERE WE ARE GOING: THE EXAMPLE OF LIDAR

Lidar, or light detecting and ranging, sensors are the optical equivalent of radar. They use a light (laser) beam, rather than a microwave radar beam, to obtain measurements of the speed, altitude, and range of a target (Helms 1998). Most of the current small-footprint (< 1 m) laser altimeters can record the time (and sometimes intensity) of at least two returns, which often correspond to the top of the canopy and the ground. Many times, however, only one return is recorded, and it may correspond to vegetation, the ground, or some cultural feature. Sophisticated processing algorithms utilizing neighborhood approaches can usually identify the bulk of the nonground returns, thus making it possible to create a bare-earth digital elevation model (DEM) with suitable interpolation techniques. Once a DEM has been created, the first returns can be interpolated to produce a canopy height model, a representation of the vertical distance from any arbitrary point on the forest floor to the topmost part of the canopy above that point. Over forested areas, the canopy height model provides canopy height at any point imaged. The canopy height model differs from photogrammetrically derived tree height in one important way—the canopy height model is a continuous representation of the canopy surface, rather than the height at any one point. It should be noted that canopy height models can be derived photogrammetrically, but many automated image-correlation algorithms function comparatively poorly over tree canopies.

From this canopy height model, and sometimes in conjunction with coregistered optical data (Gougeon and others 2001, McCombs and others 2003, Popescu and others 2004) tree, or more typically stand, volume can be determined using direct measurements corresponding to those made from photographs, namely total height, visible crown diameter, and percent crown closure and or stem counts. Some of the same problems associated with direct measurements from photographs also pertain to lidar. These are as follows: (1) lidar sensors measure the distance only to the crowns of overstory vegetation; (2) direct measurements from lidar tend to be biased (e.g., Nilsson 1996); and (3) lidar data are very expensive unless some economy of scale is realized. However, there are two substantial benefits. Firstly, the data seem to be very amenable to processing by automated techniques (at least for conifers), which increases objectivity and thus precision. Secondly, when direct measurements are used in empirical models to estimate either field-measured, e.g., total height, or derived parameters, e.g., volume or basal area, stand-level predictions are unbiased (Means and others 2000, Naesset 2002).

Again, stand volume tables require measures of height, percent crown cover, and sometimes crown diameter. Lidar-based estimates of volume require similar measurements. Determination of individual tree heights using lidar data requires identifying individual overstory stems, usually through a local maximum approach that presumes that the highest point in a local neighborhood corresponds to the top of a tree. Although this technique is effective, errors of omission or commission can occur with improper window size. Popescu and others (2002) used the height of each cell in the canopy height model to set the size of a variable window based on tree height, making possible the successful prediction (R^2 = 90 percent and 85 percent, respectively) of maximum height and mean height of dominant stems (diameter at breast height > 5 inches) even on very small 0.017-ha (0.04-acre) plots of common southeastern conifer species. As plot size increases, the need to measure individual trees decreases, and the percentage of variance explained increases. For example, Means and others (2000) used lidar-derived variables—without identifying individual trees—to explain

93 percent of the variance in height on 0.25-ha (0.6-acre) stands of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco].

Percent crown cover is particularly easy to calculate using lidar data; it is simply the number of vegetation (nonground) returns above a certain height divided by the total number of returns. Crown diameter, however, has been a little more difficult to determine, as it requires accurate stem identification as well as a way of distinguishing one crown from the adjacent one. There is substantial ongoing work in this area, but Popescu (2002) determined crown diameter for each identified tree by (1) fitting a 4-degree polynomial with least squares using singular value decomposition in both the horizontal and vertical dimensions of the canopy height model, (2) identifying critical points for each of the two fitted functions based on the first and second derivatives of a three-point Lagrangian interpolation, and (3) averaging the distance between critical points on the two perpendicular profiles. For southern pines, this technique explained 62 to 63 percent of the variance in crown diameter for the dominant trees on 0.017-ha plots (Popescu and others 2002).

Like photos, then, lidar canopy height models can serve as the base data from which important variables can be measured; namely, visible crown diameter, percent crown closure or stem count, and total height. In addition, variables unique to canopy height models, particularly those relating to the distribution of heights within any one grid cell or plot perimeter, have been successfully used as independent variables in models employed to estimate plot- or stand-level parameters (e.g., Means and others 2000, Popescu and others 2002). Examples of this type of variable include the percent crown cover or height at a specific height percentile.

Volume has been successfully calculated for conifers by use of lidar-derived measures of height, crown closure, stem density, and/or crown diameter, or of variables relating to the distribution of heights within a particular grid cell. Popescu and others (2004) was able to explain > 80 percent of the variance in volume on small (0.017-ha, 0.04-acre), heterogeneous southern pine plots in Virginia's Appomattox-Buckingham State Forest using average (per plot) crown diameter obtained by applying a lidar-derived canopy height model as the only independent variable. Means and others (2000) were able to explain 97 percent of the variance in 0.25-ha (0.6-acre) Douglas-fir plots in the H.J. Andrews Experimental Forest using the 80^{th} and 0^{th} percentile of height (the height greater than the given percentage of lidar first returns) and the 20^{th} percentile of crown cover (proportion of first returns below the given percentage of total height). Many other studies have been similarly successful in estimating volume for coniferous plots or stands on the basis of lidar data.

Lidar-based forest measurements, while based on many of the same principles as photo-based measurements, such as using crown diameter as a surrogate for stem diameter, are typically more accurate and less biased than photo-based measurements. As with aerial photographs, bias exists because laser altimeters see only portions of the crowns of dominant overstory trees. However, increased levels of automation have led to substantial reductions in both interpreter-specific bias and the need for specialized training. Furthermore, lidar canopy height models afford the characterization of the whole population, rather than just a sample, of the dominant overstory trees in a specific area of interest. However, lidar data are still quite expensive for small areas on a per-unit basis, so lidar-based inventory, like photo analog inventory, is cost-effective primarily for large and/or relatively inaccessible areas. This description hardly characterizes the typical southern forest landscape, which is dominated by the holdings of nonindustrial private forest landowners.

THE LIKELY FUTURE NEED FOR ADDITIONAL REMOTELY SENSED DATA

The most commonly used standard for all remotely estimated forest measurements is field inventory, which typically employs remotely sensed data only for stratification. Thus in order to be widely accepted and used, remotely derived estimates of important forest biophysical parameters must have the same level of precision and accuracy as field-derived measurements, and be less expensive than they are. The lack of widespread adoption of these new technologies is de facto proof that this standard has not yet been met. As with all technological innovation, however, the cost per unit of information derived from remotely sensed data will continue to decrease, thus increasing their potential use for traditional inventory needs as a tradeoff with field costs. Another factor to be considered is that increasing forest productivity will require more remotely sensed data. Organizations will be willing to spend more for information if this expenditure results in increased productivity.

JUSTIFYING INCREASED USE OF REMOTELY SENSED DATA: THE EXAMPLE OF INTENSIVE (AND/OR SITE-SPECIFIC) FOREST MANAGEMENT

Most of the preceding discussion has focused on traditional assessment and inventory, an ongoing need whose importance is not likely to diminish in the near future. However, inventories using existing remote sensing technologies suffer, on the whole, from being more expensive and less accurate than field inventory for the small tracts that are coming to dominate the southern forest landscape. Thus they are not widely used in most instances. However, traditional assessment and inventory is only part of a larger picture of forestry information needs—needs that are likely to become urgent as management for increased production intensifies on some private tracts and the demands for multiple uses continue to drive public forest management. The following discussion addresses the potential effect of more intensive management of portions of the private land base on the future of forestry remote sensing.

Partially as a result of increased demand, and partially as a consequence of effective reductions in the land base resulting from (1) permanent land use conversion, (2) changes in public land management priorities, and (3) changes in the motivations and attitudes of nonindustrial private forest landowners, forest managers are increasingly being called upon to produce more wood or fiber from less land with shorter rotations. This challenge is being met with silvicultural tools that have agricultural analogs, such as site preparation, nutrient management, release from competition, and improved genetic stocks. The agricultural model can be pushed even farther as management intensifies; it can be argued that intensive forest management is as suited for precision forestry as intensive farm management is suited for precision agriculture. Mulla's (1997) definition of precision agriculture is as follows:

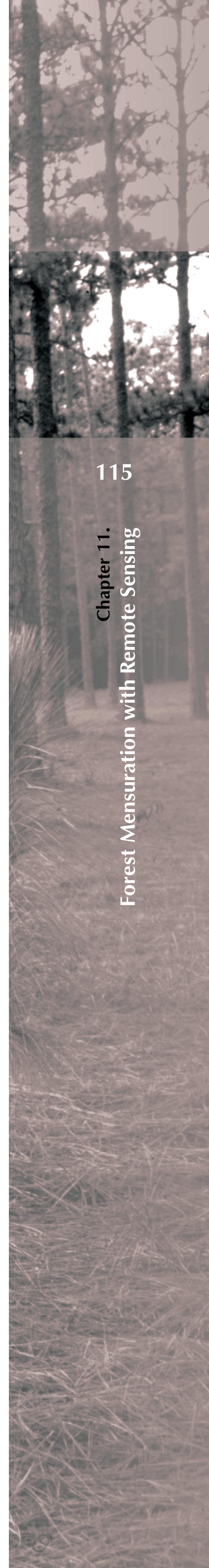
> Precision agriculture is an approach for subdividing fields into small homogeneous management zones where fertilizer, herbicide, seed, irrigation, drainage, or tillage are custom-managed according to the unique mean characteristics of the management zone.

Precision forestry is analogous to precision agriculture in that traditional management units (forest stands are analogous to agricultural fields) must be subdivided for specific prescription of silvicultural treatments; e.g., site preparation, fertilization, and release from competition.

However, there are some important differences between precision agriculture and precision forestry. Forest stands are typified by the (1) important array of public goods provided, such as clean water, wildlife habitat, carbon storage, and recreational opportunities; (2) much longer rotations required; (3) widespread use of helicopters for spraying; (4) species; (5) minimal use of irrigation; and (5) general lack of effective yield monitoring at the time of harvest. This last difference cannot be seen as problematic for precision forestry, as many experts (e.g., Pierce and Nowak 1999) agree that yield-based determination of preharvest spatial variability is a temporary solution, to be replaced by the use of remote sensing technologies. Given the relative importance and degree of development of forestry applications of remote sensing, precision forestry should not need to evolve through the yield-monitoring stage. Furthermore, precision forestry subsumes precision silviculture, precision inventory, precision growth and yield, and precision harvest scheduling, creating a complete information pathway. Remote sensing and related geospatial information technologies provide the inventory information necessary to (1) define the treatment unit for each silvicultural prescription and (2) provide the within-stand measurements of forest biophysical parameters necessary for growth-and-yield models and related harvest scheduling models.

Landowner records usually provide information on stand type, age, initial stocking density, and site preparation. Required parameters suited to remote estimation include leaf area index, current stem density, crown diameter, height, and species or species group. The last is especially helpful for timing and/or locating need for release from competition. Foliar nutrients can also be assessed using airborne hyperspectral, or, potentially, tailored handheld instruments (e.g., Bortolot and Wynne 2003), though such approaches have so far not been cost-effective when compared with lab analysis of foliar samples.

The relative need for and cost:benefit ratio of remotely sensed and precisely located *in situ* data must drive both the research in and the adoption of appropriate technologies. Furthermore within the wide variety of remotely sensed data that are well suited for precision forestry applications, researchers must find the best combination of



spectral resolution, spatial resolution, and canopy height information for estimating each required parameter. Data types include but are not limited to (1) canopy height models derived from lidar or digital photogrammetry, (2) high spatial-resolution optical data, (3) moderate-resolution multispectral data, and (4) hyperspectral data at a variety of spatial resolutions. Research being carried out by Government, industry, nongovernmental organizations, and universities is providing the base for improved integration of remote sensing in forest management. However, the gap between remote sensing research and accessible, useful information is still too large.

FROM DATA TO APPLICATIONS

It has been said that production forestry organizations make or lose money near the bottom rungs of the organizational ladder, not at the top (Smith and others 2003). Most field foresters have substantial experience with aerial photographs but have neither the time for nor the interest in processing images from digital remotely sensed data. In many cases, given the widespread use of and familiarity with aerial photographs in forestry, digital images can be subjectively analyzed for the wide variety of applications mentioned in this chapter. However, it can be argued that this model limits the potential utility of remote sensing to forestry, as it may not provide any net increase in information. The kinds of sensors that will help facilitate a net increase in forestry information derived from remotely sensed data include laser altimeters and hyperspectral scanners. The data these sensors yield will only be suited, in their raw form, for use by image analysts or other experts in the same field. Field foresters generally do not have the experience to qualify as experts in image analysis. They "require information, not images . . . ." (Oderwald and Wynne 2000).

The National Research Council, in their recent study on "Transforming Remotely Sensed Data into Information and Applications" (2001), identified three gaps that must be bridged to develop effective civilian applications of remote sensing:

1. The gap between raw data and the information needed by end users
2. The gap in communication and understanding between end users and those with remote sensing technical experience and training
3. The financial gap between data acquisition and usable applications

While these identified gaps apply across the spectrum of end users, they are particularly relevant for forestry. The report goes on to make the following recommendations, which are also quite pertinent to forestry:

1. Publicly available studies identifying the full range of short-term and long-term costs and benefits of remote sensing applications should be carried out by a full range of public and private stakeholders.
2. Cognate Federal Agencies should help fund and foster a wide variety of remote sensing training materials and courses.
3. Staff exchanges should occur between remote sensing users and producers.
4. Graduate fellowships and research assistantships should be sponsored by land grant, sea grant, and agricultural extension programs to encourage work at agencies that use remote sensing data.
5. Federal agencies need to expand their support for applied remote sensing research.
6. Formal mechanisms should be established to enable applications users to advise private and public sector providers on their requirements.
7. Data preservation is important and should be routinely addressed by all data providers.
8. Internationally recognized formats, standards, and protocols should be used whenever possible to facilitate data exchange and ease of use.

It is evident from the foregoing that forestry is not the only application area where there is a large gap between obtaining remote sensing data and translating the data into useful information. It is evident that concrete recommendations for bridging this gap have been made. As a community of forest scientists and managers, it is our responsibility to identify information needs of the future, and to make sure that adequate methods of meeting these needs can be made available.

LITERATURE CITED

Avery, T.E. 1978. Forester's guide to aerial photo interpretation. Washington, DC: U.S. Department of Agriculture, Forest Service. 41 p.

Avery, T.E.; Burkhart, H.E. 2002. Forest measurements. Boston: McGraw-Hill. 456 p.

Bortolot, Z.J.; Wynne, R.H. 2003. A means of spectroscopically determining the nitrogen content of green tree leaves measured at the canopy level that requires no *in situ* nitrogen data. International Journal of Remote Sensing. 24(3): 619–624.

Brown, T.L.; Lassoie, J.P. 1998. Entry-level competency and skill requirements of foresters: what do employers want? Journal of Forestry. 96(2): 8–14.

Food and Agriculture Organization of the United Nations. 1997. State of the world's forests—1997. Rome. [Number of pages unknown].

Gougeon, F.A.;. St-Onge, B.A; Wulder, M.; Leckie, D.G. 2001. Synergy of airborne laser altimetry and digital videography for individual tree crown delineation. Canadian symposium on remote sensing. Sainte-Foy, Quebec, Canada: [Publisher unknown]. 7 p.

Helms, J.A., ed. 1998. The dictionary of forestry. Bethesda, MD: Society of American Foresters. 210 p.

Lund, H.G.; Befort, W.A.; Brickell, J.E. [and others]. 1997. Forestry. Manual of photographic interpretation. Bethesda, MD: American Society for Photogrammetry and Remote Sensing: 399–440.

McCombs, J.W.; Roberts, S.D.; Evans, D.L. 2003. Influence of fusing lidar and multispectral imagery on remotely sensed estimates of stand density and mean tree height in a managed loblolly plantation. Forest Science. 49(3): 457–466.

Means, J.E.; Acker, S.A.; Fitt, B.J. 2000. Predicting forest stand characteristics with airborne scanning lidar. Photogrammetric Engineering & Remote Sensing. 66(11): 1367–1371.

Mulla, D.J. 1997. Geostatistics, remote sensing, and precision farming. In: Lake, J.V.; Bock, G.R.; Goode, J.A., eds. Precision agriculture: spatial and temporal variability in environmental quality. [Location of publisher unknown]: John Wiley. [Number of pages unknown].

Naesset, E. 2002. Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data. Remote Sensing of Environment. 80: 88–99.

National Research Council. 2001. Transforming remote sensing data into information and applications. Washington, DC: National Academy Press. 75 p.

Nilsson, M. 1996. Estimation of tree heights and stand volume using an airborne lidar system. Remote Sensing of the Environment. 56: 1–7.

Oderwald, R.G.; Wynne, R.H. 2000. Field applications for statistical data and techniques. Journal of Forestry. 98(6): 58–60.

Olson, C.E., Jr. 1960. Elements of photographic interpretation common to several sensors. Photogrammetric Engineering. 26(4): 651–656.

Paine, D.P. 1981. Aerial photography and image interpretation for resource management. New York: John Wiley. 571 p.

Pierce, F.J.; Nowak, P. 1999. Aspects of precision agriculture. Advances in Agronomy. 67: 1–85.

Popescu, S.C. 2002. Estimating plot-level forest biophysical parameters using small-footprint airborne lidar measurements. Blacksburg, VA: Virginia Polytechnic Institute and State University, College of Natural Resources. 155 p.

Popescu, S.C.; Wynne, R.H.; Nelson, R.F. 2002. Estimating plot-level tree heights with lidar: local filtering with a canopy-height based variable window size. Computers and Electronics in Agriculture. 37: 71–95.

Popescu, S.C.; Wynne, R.H.; Nelson, R.F. 2003. Measuring individual tree crown diameter with lidar and assessing its influence on estimating forest volume and biomass. Canadian Journal of Remote Sensing. 29(5): 564–577.

Popescu, S.C.; Wynne, R.H.; Scriviani, J.A. 2004. Fusion of small footprint lidar and multispectral data to estimate plot-level volume and biomass in deciduous and pine forests in Virginia, U.S.A. Forest Science. 50(4): 551–565.

Sader, S.A; Vermillion, S. 2000. Remote sensing education: an updated survey. Journal of Forestry. 98(4): 31–37.

Smith, J.L.; Clutter, M.; Keefer, B.; Ma, Z. 2003. Special commentary: the future of digital remote sensing for production forestry organizations. Forest Science. 49(3): 455–456.

Spurr, S.H. 1960. Photogrammetry and photo-interpretation with a section on applications to forestry. New York: Ronald Press. 472 p.

U.S. Department of Agriculture, Forest Service. 1998. Changing economics of the national forest timber sale program. Washington, DC. [Number of pages unknown].

World Bank. 1992. World development report 1992: development and the environment. Oxford: Oxford University Press. [Number of pages unknown].

Wynne, R.H.; Oderwald, R.G.; Reams, G.A.; Scriviani, J.A. 2000. Optical remote sensing for forest area estimation. Journal of Forestry. 8–14.